Designing UltraHigh Field Magnets for NMR and MRI

Joseph V. Minervini
Massachusetts Institute of Technology
Plasma Science and Fusion Center
Cambridge, MA

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Outline

- Design and manufacturing issues with high very high field and large volume magnets
- Why high current conductors
- Types of high current conductors
- Joints (splices) and Terminations
- Coil manufacturing issues
- Operational issues

Design and manufacturing issues with high very high field and large volume magnets

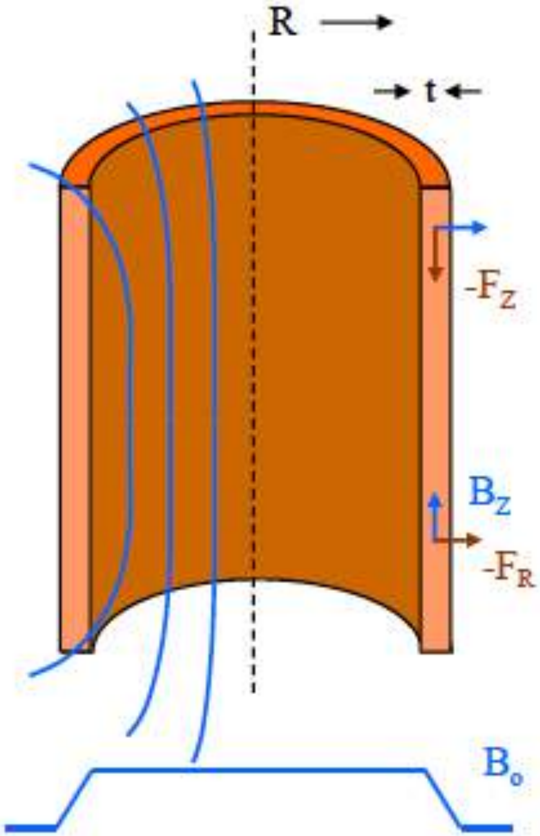
- Very high stored energy
  - Very high forces and stresses ⇒ structure
  - Quench protection ⇒ heating and voltage
- Cooling and stability over large volumes
- Large coil manufacture
  - Long conductor lengths
  - Conductor splices
  - Heat treatment for Nb_3Sn or Bi-2212
  - Nb_3Sn and Bi-2212 are very strain sensitive

Fusion and HEP Have Experience with Large High Field Magnets

ITER CSMC: B = 13 T, E = 640 MJ

ITER TF: B = 11.8 T, E = 41 GJ (18 Coils)

Magnetic Forces and Stresses



Approximately for a long thin solenoid

central field $B_o = \mu_o NI = \mu_o Jt$

total outward force on unit area of wall of coil $F = \frac{B_o}{2} Jt = \frac{B_o^2}{2\mu_o}$

'magnetic pressure' $P_m = \frac{B_o^2}{2\mu_o}$

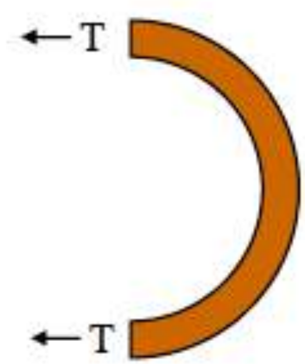
at 5T, P_m~ 10MPa

at 10T, P_m~ 40MPa

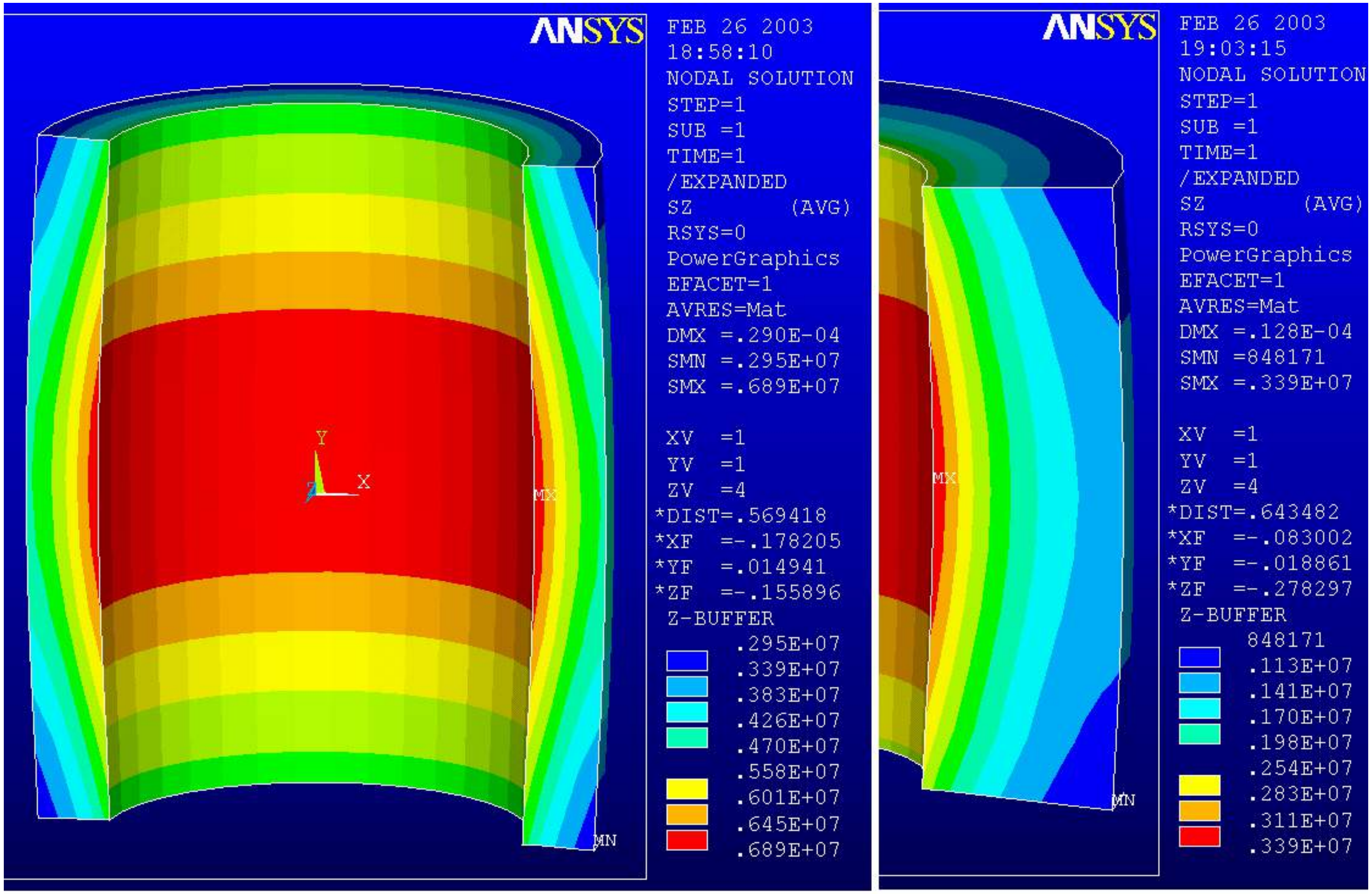
At 20 T P = 160 MPa

total hoop tension $T = \frac{B_o^2}{2\mu_o} R$

mean hoop stress $\sigma_m = \frac{B_o^2}{2\mu_o} \frac{R}{t}$



Hoop Stress in a Finite Solenoid



Hoop Stress in a Finite Build Solenoid

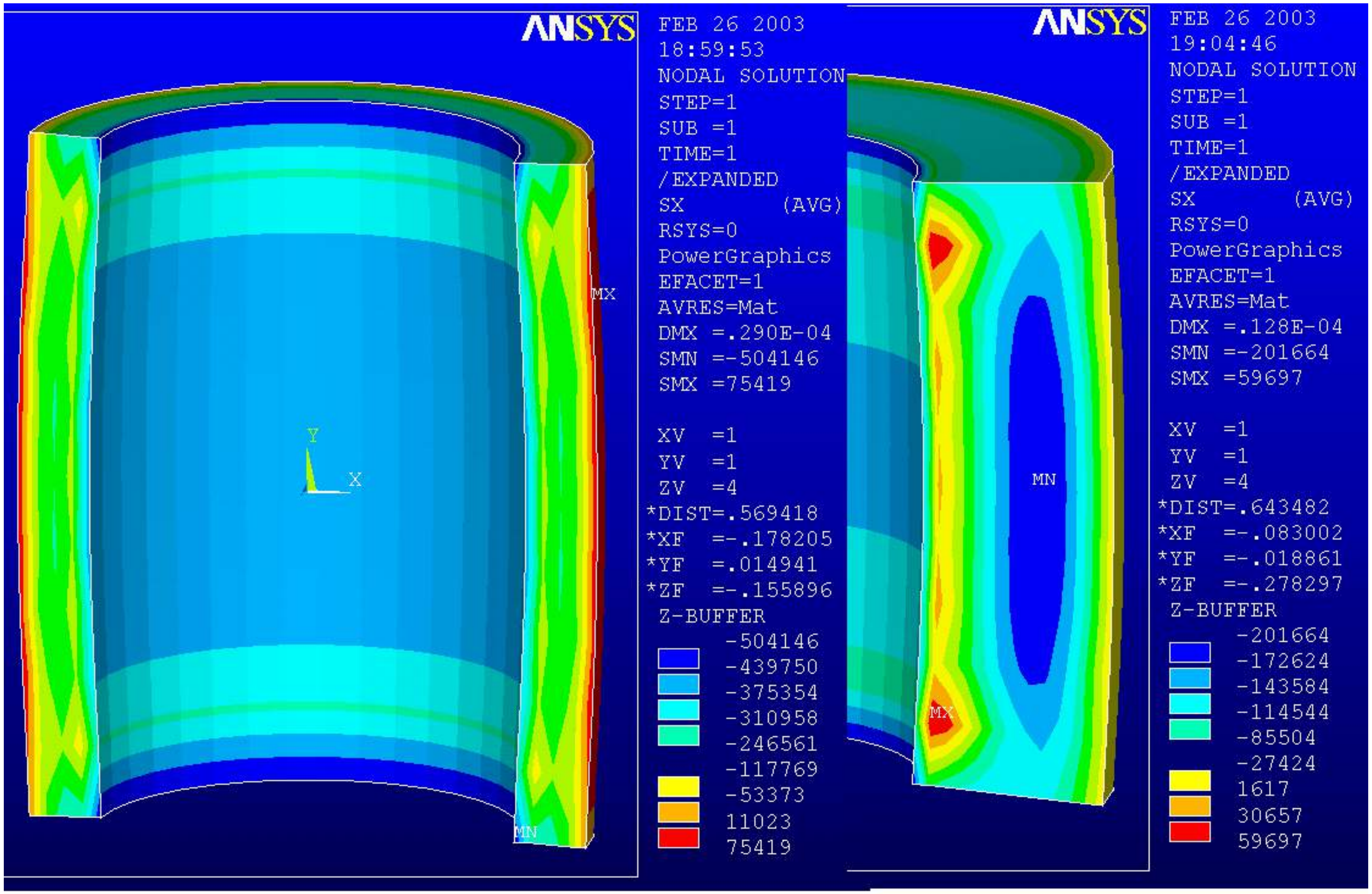
R	Z	dR	dZ
.3	0	.1	1.0 (m)

Current Density=5kA/cm^2
Bmax=5.24 Tesla

R	Z	dR	dZ
.5	0	.3	1.0 (m)

Current Density=1.67 kA/cm^2
Bmax=5.015 Tesla

Radial Stress in a Finite Solenoid



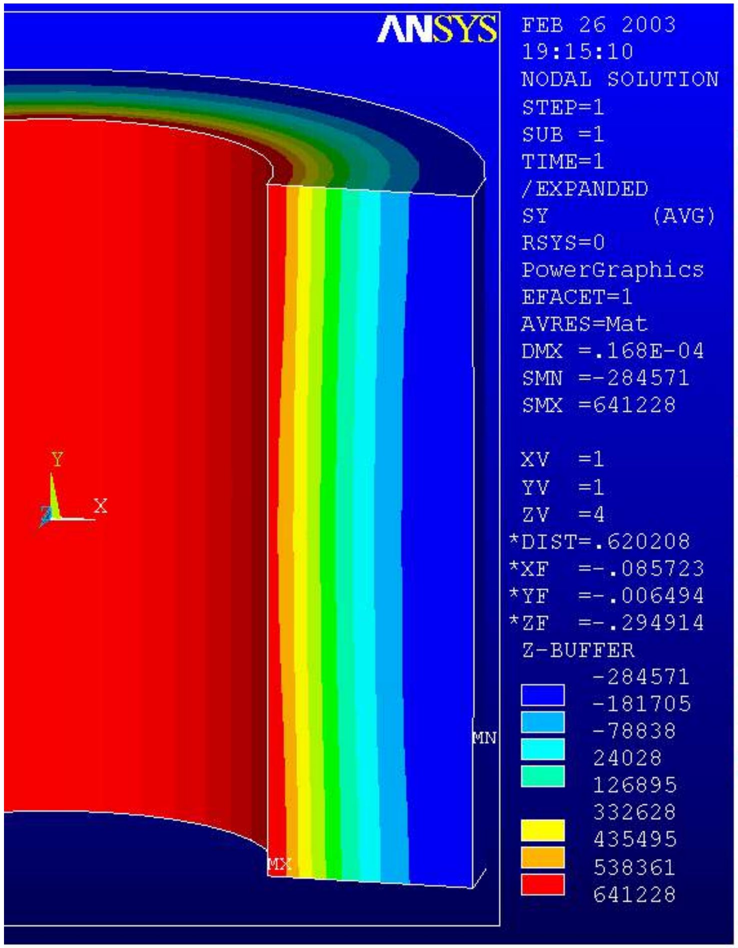
Radial Stress in a Finite Solenoid

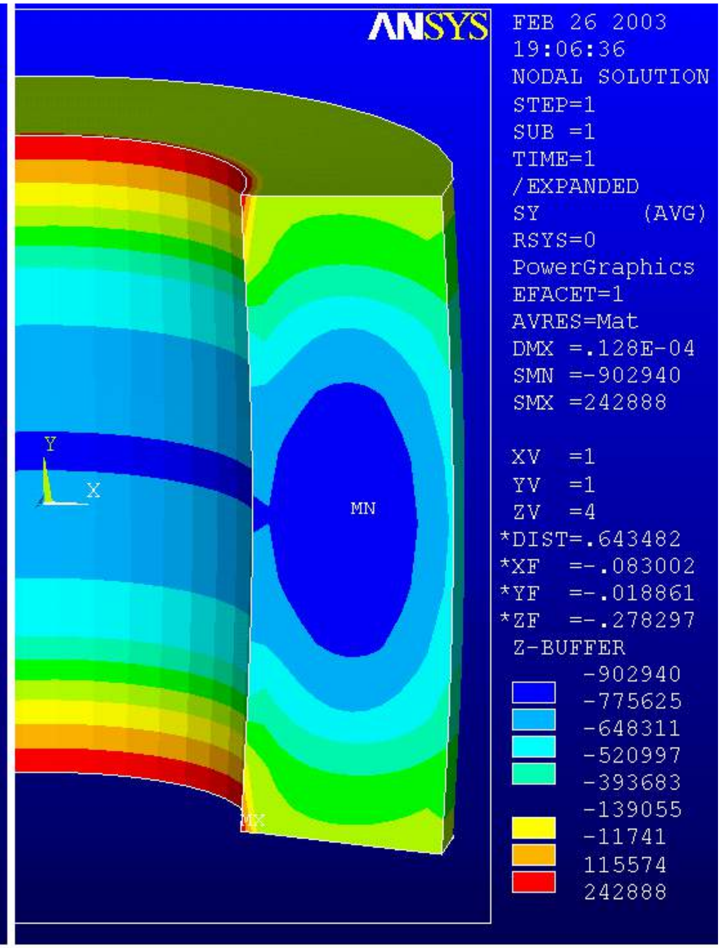
R Z dR dZ
.3 0 .1 1.0 (m)
Current Density=5kA/cm^2
Bmax=5.24 Tesla

The Tension Stress on the OD of the Thin Sheet Solenoid is a finite mesh effect. Note Tension near ID of larger build coil

R Z dR dZ
.5 0 .3 1.0 (m)
Current Density=1.67 kA/cm^2
Bmax=5.015 Tesla

Axial Stress Comparison
Infinite vs Finite





Infinite Solenoid

R Z dR dZ

.3 0 .1 >>1.0 (m)

Current Density=5kA/cm^2

Bmax=5.478 Tesla

Vertical Stress Comparison

Finite Solenoid

R Z dR dZ

.5 0 .3 1.0 (m)

Current Density=1.67 kA/cm^2

Bmax=5.015 Tesla

Structural Materials Required to be Integrated into the Windings

- Reduces coil current density
  - Increased coil size
- Compatibility of structural materials of superconducting and insulating materials
  - Thermal stresses on cooldown/warmup/quench
- Increased manufacturing complexity
  - Special tooling and winding procedures

Strain Sensitivity and Thermal Contraction

- For wind and react Nb_3Sn coils, the difference in thermal contraction of superconductor reaction heat treatment temperature to operating temperature can significantly affect the critical current

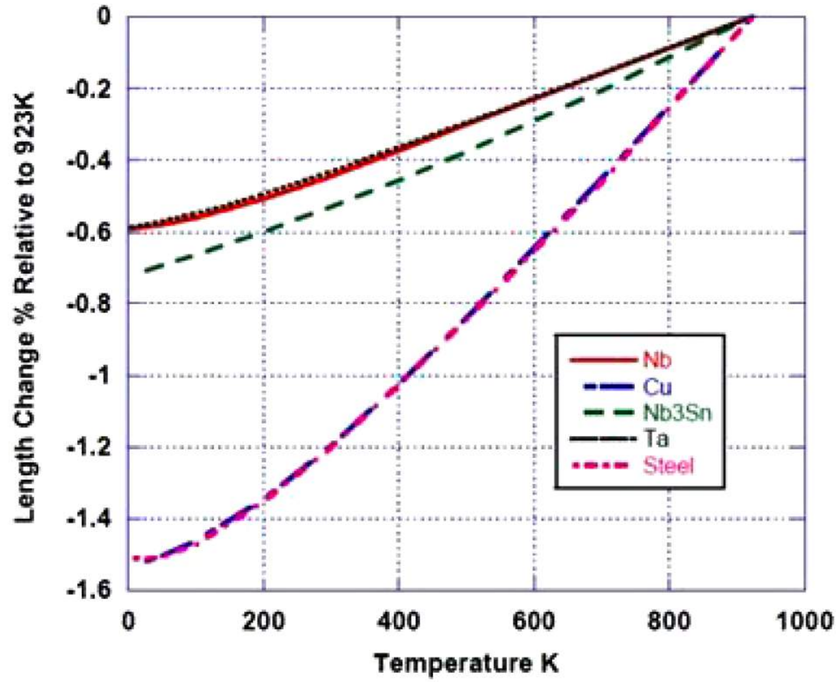
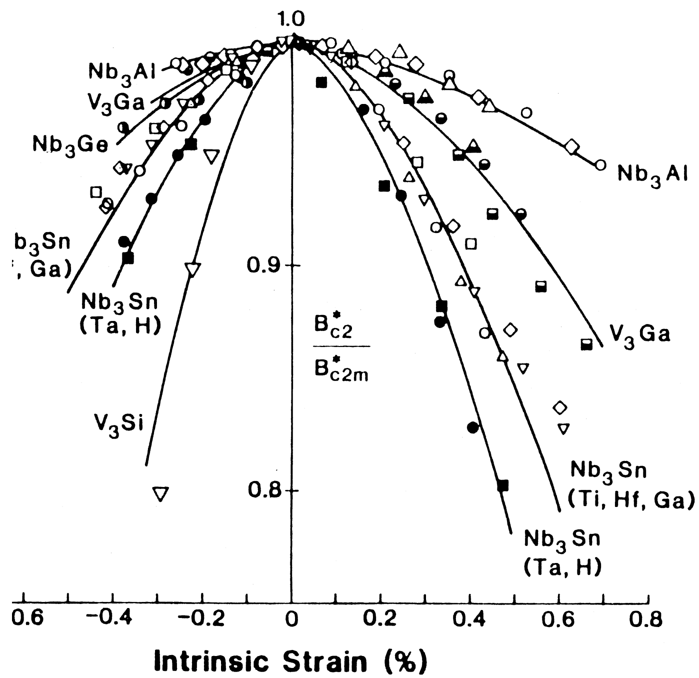


Figure 4. Integrated thermal shrinkage coefficients of various materials relevant for ITER-type cable-in-conduit conductor analyses.

Cu, bronze, Nb_3Sn, Ta,



Why Multistrand Conductors?

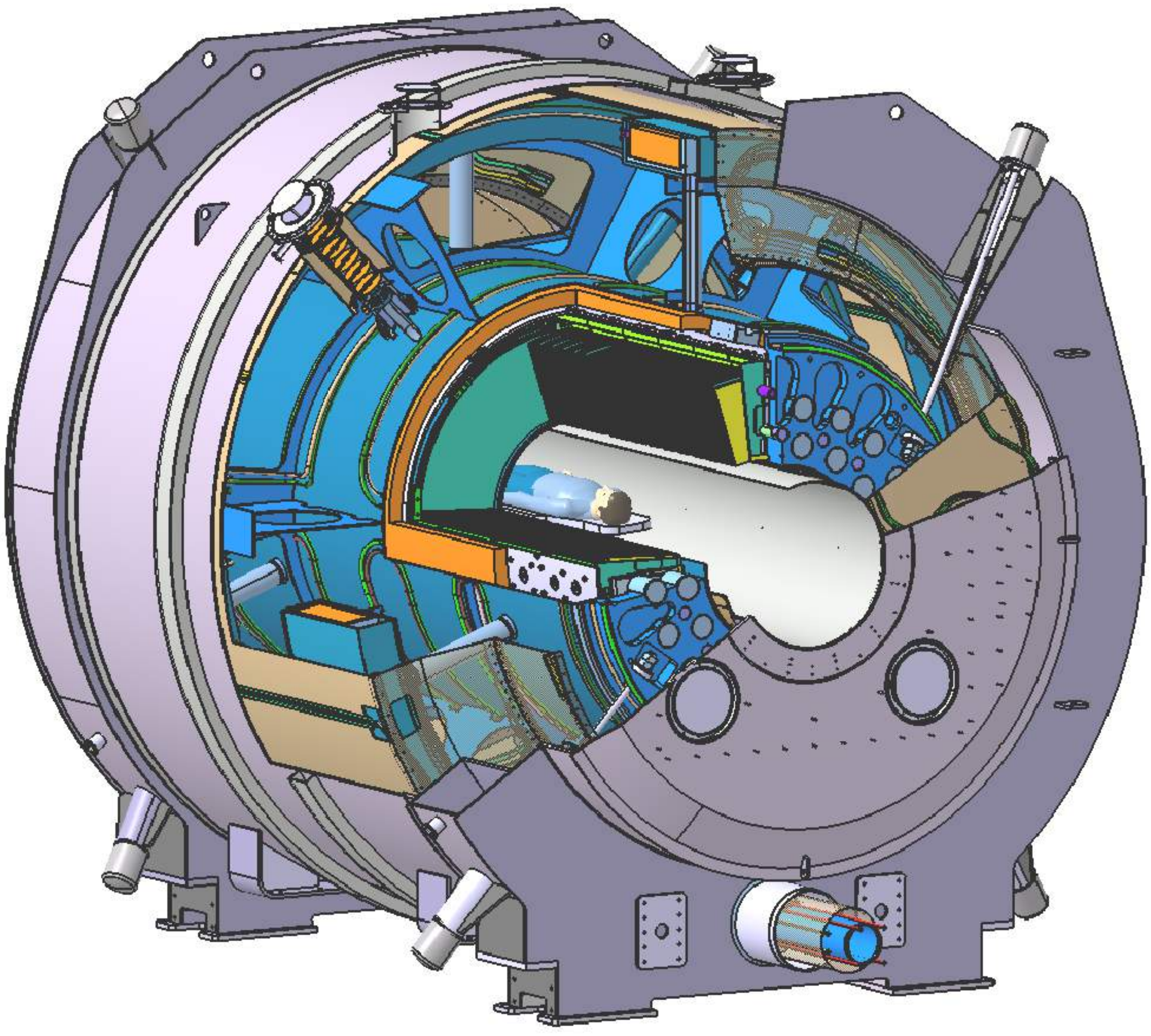
- Whether LTS or HTS most conductors have dimensions of order 1 mm for:
  - Electromagnetic and thermal stability
  - Reduction in magnetization and ac losses
- They all carry operating currents of some 10's to hundreds of amps depending on B.
- *Bundling these small wires into cables is necessary if larger currents are required*
  - A few kA's to 10's of kA

Why Higher Currents?

- For large scale magnets
  - Generate high magnetic fields over large volumes
    - Easier to fabricate coils using a small number of large conductors rather than a large number of small conductors, shorter piece length
  - For issues related to quench protection for magnets with high stored energy
    - Ability to redistribute current in case of strand quench or local defect
    - Lower coil inductance
  - ~~For reduction of ac losses in ac, pulsed, or ramped magnets~~
  - For better electro-thermal stabilization in coils where the conductors are in direct contact with fluids

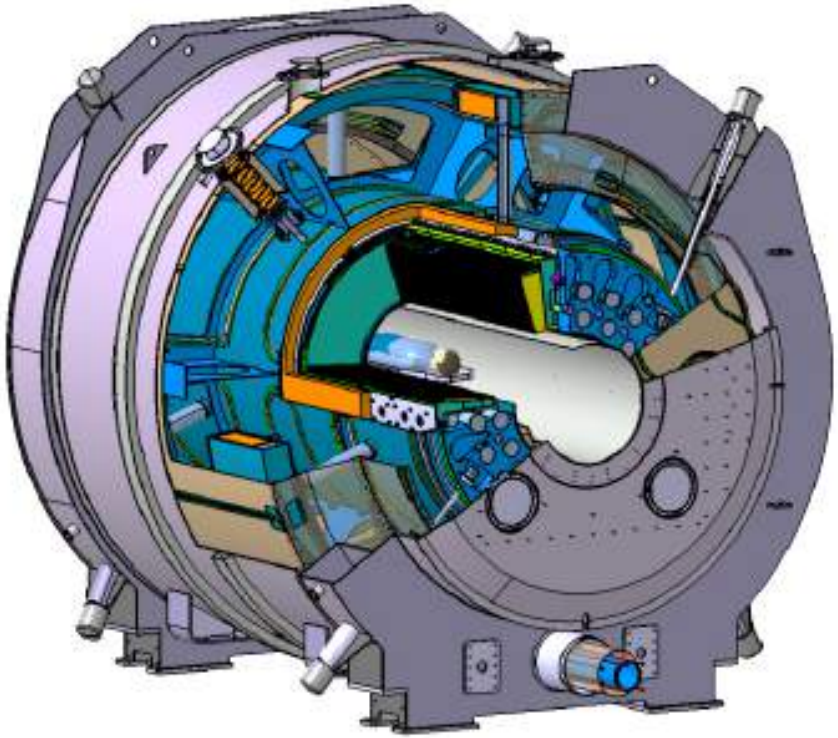
Why High Current Conductors?

An example based on stored energy



ISEULT-Neurospin 11.7 T MRI Magnet

Iseult 11.7 T whole body MRI Magnet



- **magnet windings:**
  - ***main coil (green)***
  - ***cryoshim coils (orange)***
  - ***shielding coils (orange)***
- **mechanical structure at 1.8 K (blue)**
- **cryostat (grey)**

Stored Energy	338 MJ
Inductance	308 H
Current	1483 A
Overall Length	5.2 m
Overall diameter	5 m
Weight	132 t

Magnet main parameters

- B0 / Aperture 11.75 T / 900 mm
- Field stability 0.05 ppm/h
- Homogeneity < 0.5 ppm on 22 cm DSV
- 170 wetted double pancakes for the main coil
- 2 shielding coils to reduce the fringe field
- **NbTi** conductor @ 1.8 K

Why High Current Conductors?

An example based on stored energy

- The ISEULT magnet has a peak field ~12 T at the windings.
- The magnet system stores **38 MJ** of magnetic energy with an inductance of 308 H!
- If the stored energy is *E*, quench dump time *constant is t* and operating current is *I*, *then* the dump voltage is

$$E = \frac{1}{2} L I^2 \qquad V = \frac{L\,I}{t} = \frac{2\,E}{I\,t}$$

TABLE I SEHT AND ISEULT - ELECTRICAL PARAMETERS

Parameters	Unit	Seht	Iseult
Magnetic field	T	8	11.75
Magnet resistance, *Rmag*	nΩ	100	~200
Inductance, *Lmag*	H	44	308
External dump resistor, R_D	Ω	2	2.7
Time constant, τ_{mag}	s	22	114
Nominal current, *Imag*	A	880	1483
Voltage discharge max, *Ud max*	V	1800	4000

Quench: ISEULT Magnet Contains 7200 liters of LHe

ISEULT Uses Multistrand Cable-In-Channel

CONDUCTOR MECHANICAL BEHAVIOUR

Iseult :

170 Double Pancakes (DP)

1000mm/1900mm diameter

Insulation spacer with helium channels

NbTi conductor operating at 1500 A / ≈12 T / 1.8 K

Azimuthal stress 170 MPa

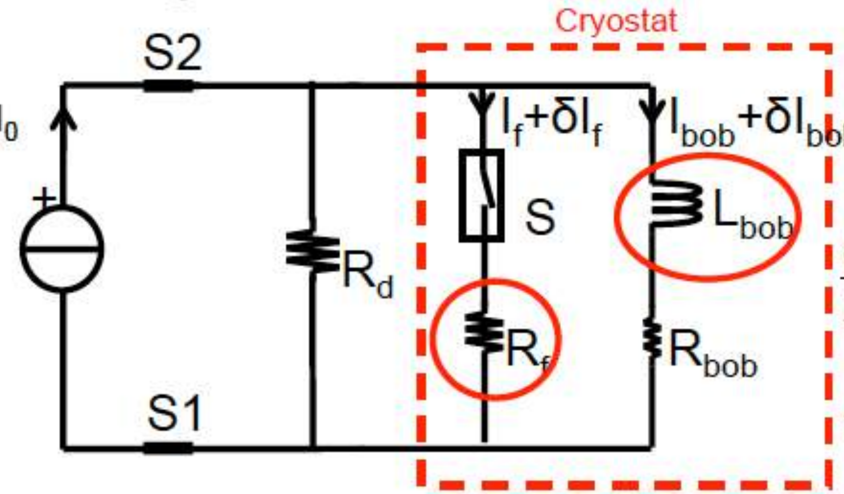
Axial stress 110 Mpa

=> A qualification prototype request: R0 then R1 installed in the 8T test facility (at 4T) with a maximum diameter 480 mm => 5000 A max to reach the target azimuthal stress

High current magnets must be driven by very stable power supply (no PCS)

STABILITY: 0.05 PPM/H WITH A ELECTRICAL SUPPLY

Use a semi-persistent mode (Oxford patent) by installing a current limiter rather than a superconducting switch.

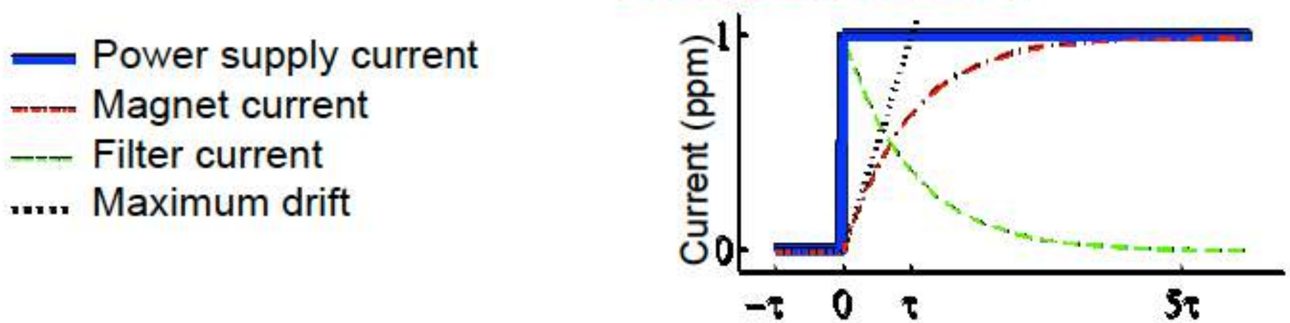


$R_d >> R_f >> R_{bob}$

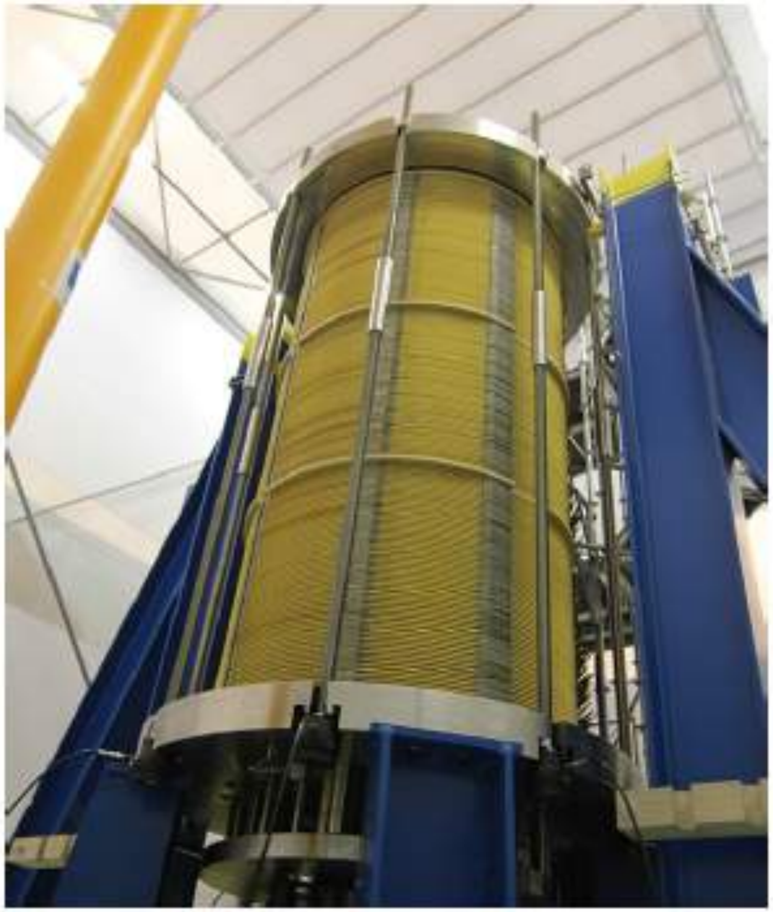
Maximum drift

$$\left.\frac{\delta I_{bob}}{I_0.\delta t}\right|_{t=0} = \frac{\delta I_0}{I_0.\tau}$$

$$\tau = \frac{L_{bob}}{(R_{bob}+R_f)}$$



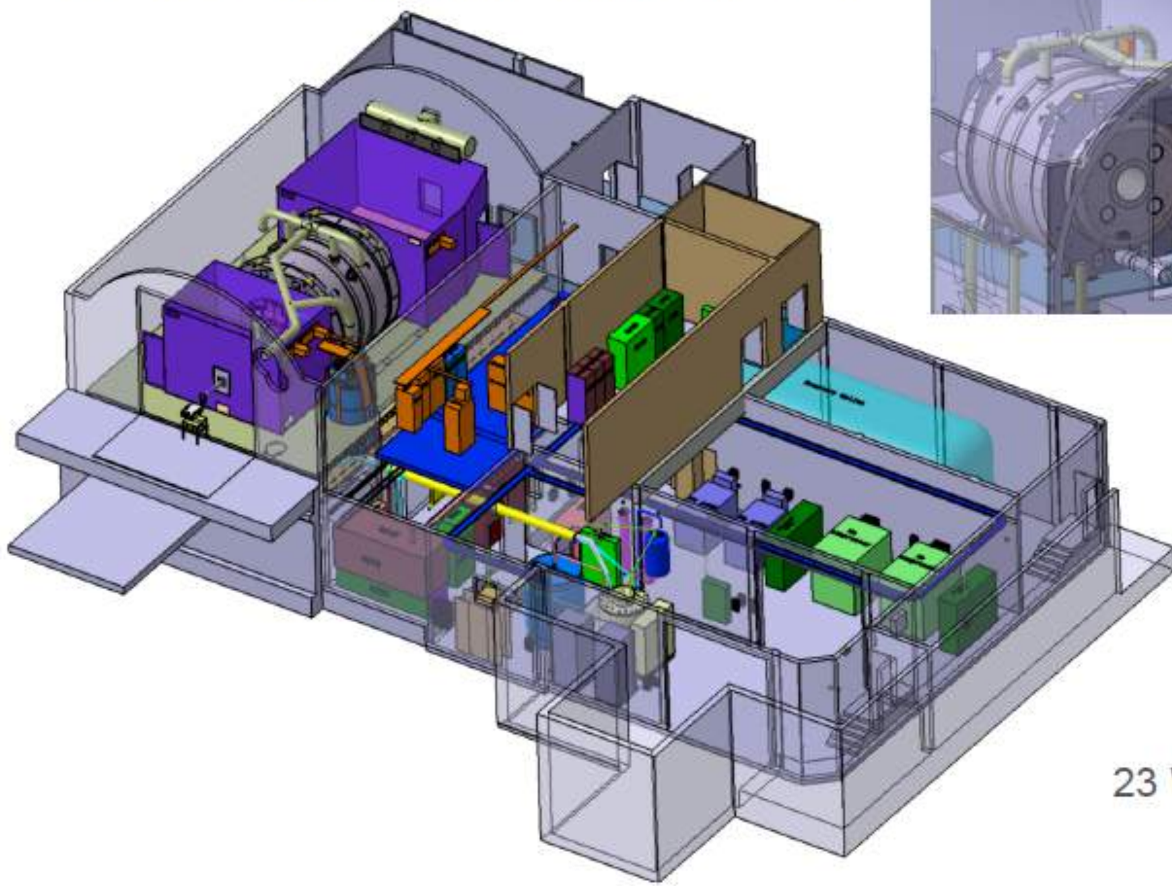
UHF MRI Magnets are huge

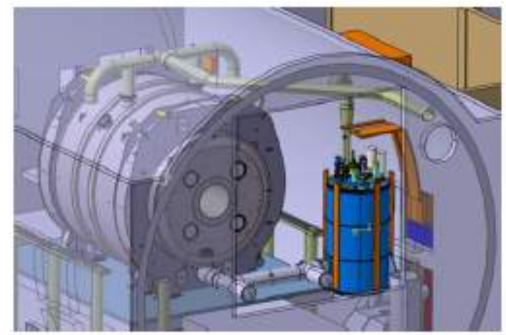


Very Large Facilities, Infrastructure and Support Team are Required

PREPARATION OF NEUROSPIN SITE

Ready to received the magnet for the end of 2015





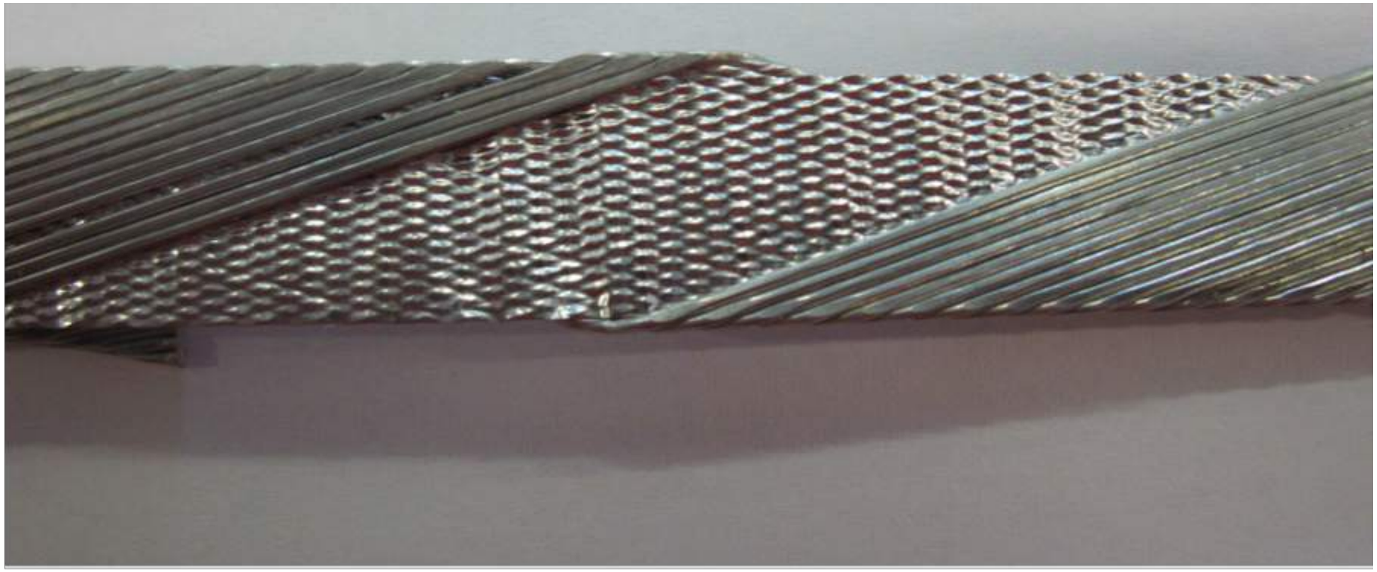
23 W at 1.8 K

Types of High Current Conductors

- Single stage
  - Typically Rutherford cable
  - Or Rutherford Cable in Stabilizer (Cu or Al)
  - Or Rutherford Cable in Channel (Cu)
  - Currents ~2 kA to ~20 kA
  - 8 to 36 strands
- Multi-Stage
  - Typically 2 to 6 stages
  - 3, 4, 5, 6, 6-around-1, etc. strands per stage
  - Different types of transposition
  - Currents ~ 5 kA to ~ 100 kA

Rutherford Cables

- Sometimes the strands are cabled around cores
  - Add mechanical strength
  - ~~Reduce coupling losses, particularly for fast cycled magnets~~

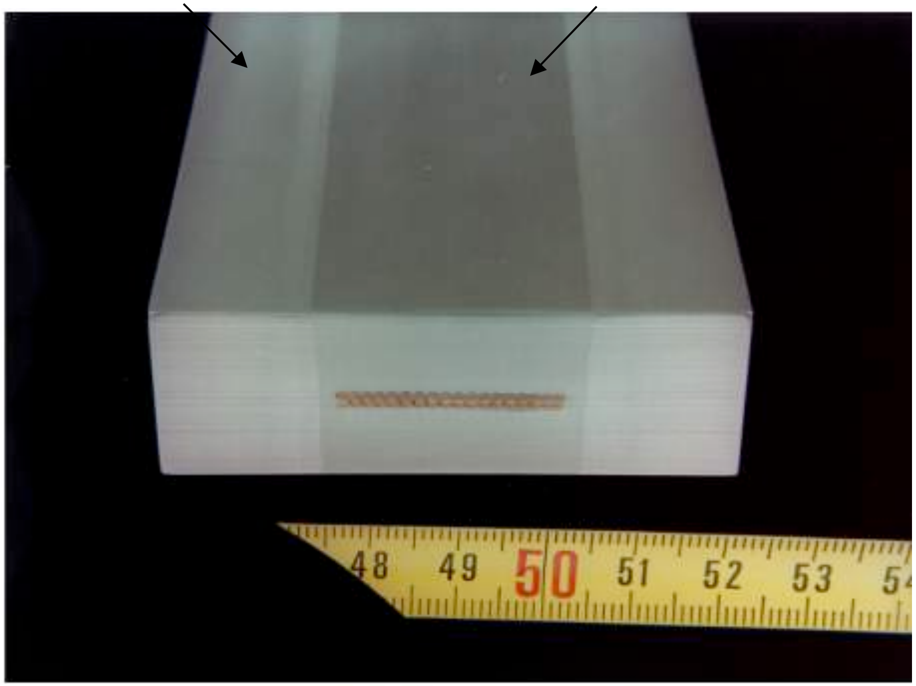


Cored Nb-Ti cable trial for the CRISP SIS-300 prototype.

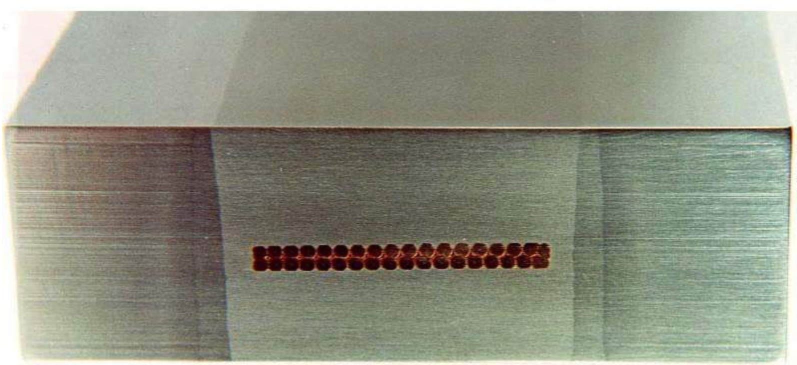
Rutherford Cabling in Extruded Aluminum

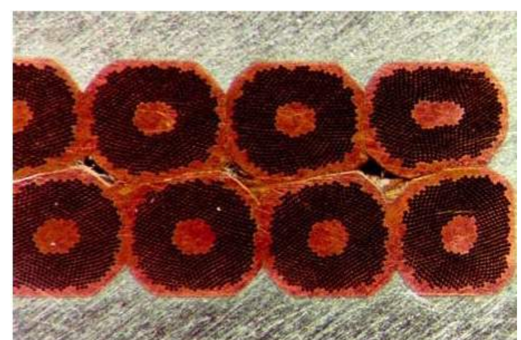
Aluminum alloy reinforcement

Aluminum stabilizer



CMS Conductor

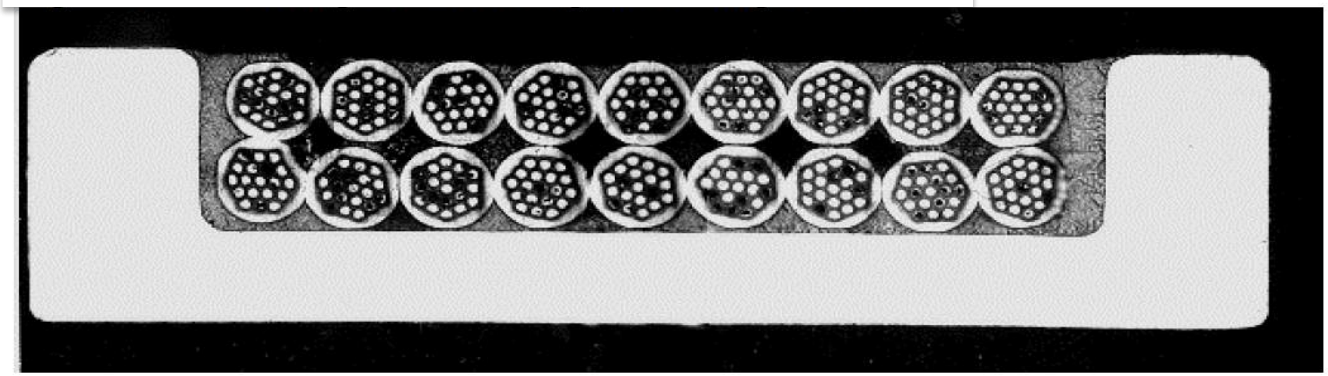




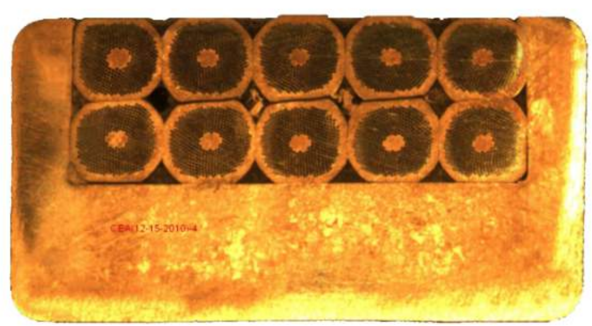
Rutherford Cable-in-Channel

Cable-in-channel conductor for the Levitated Dipole Experiment (LDX) floating coil

Nb_3Sn, 2 kA at 5 T. React cable and solder in channel.



Cable-in-channel conductor for ISEULT 11.7 T Whole Body MRI Magnet NbTi



Example of a Forced-Flow Conductor

EURATOM Large Coil Test (LCT) Conductor (c. 1980s)

Rutherford Cable soldered to insulated SS core

Conductor force-cooled by Supercritical He

MF Nb-Ti/Cu composites

SS Jacket seam-welded

Cable-in-Conduit-Conductor (CICC)

Cabled strands of superconductor encased in a conduit, which provides mechanical strength and through which single-phase cryogen (generally helium) is forced to provide cooling to the superconductor

Advantage

- Integrates key requirements of a superconductor—current-carrying capacity; stability & protection; low AC losses; mechanical integrity, turn insulation—in a single conductor configuration.

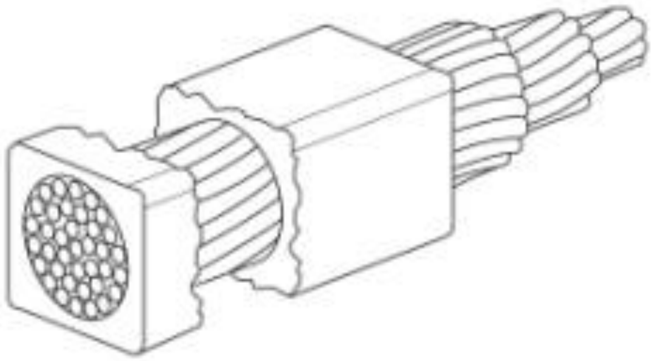
Disadvantage

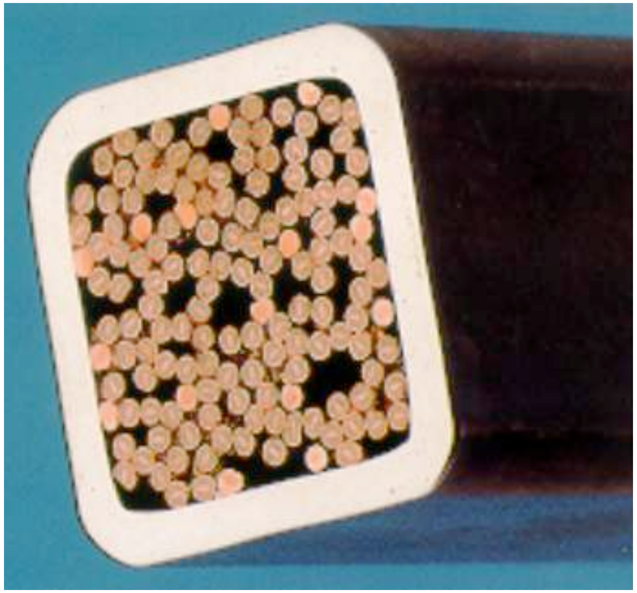
- Because of the non-current carrying space occupied by the conduit and cryogen, I_{op} should be "large" to keep J_{over} "reasonable." Generally, I_{op} >10 kA; occasionally I_{op}> a few kA.

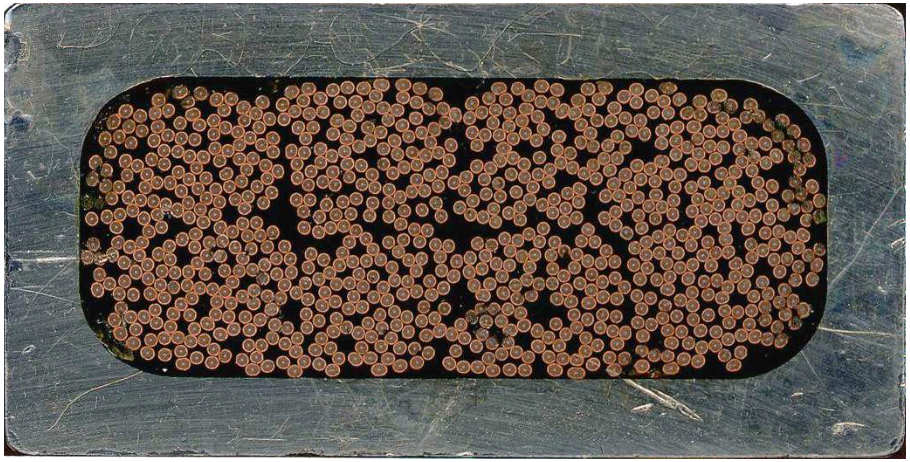
Suitable Applications

- "High" field and "large" volume magnets, i.e., fusion; SMES.

Cable-in-Conduit-Conductor (CICC)







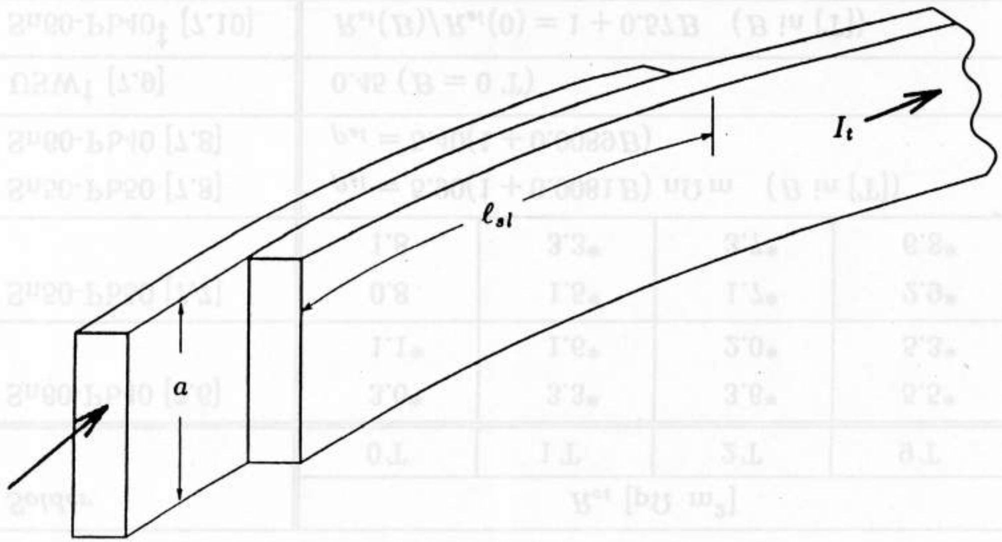
CICC Issues: Splices and Terminations

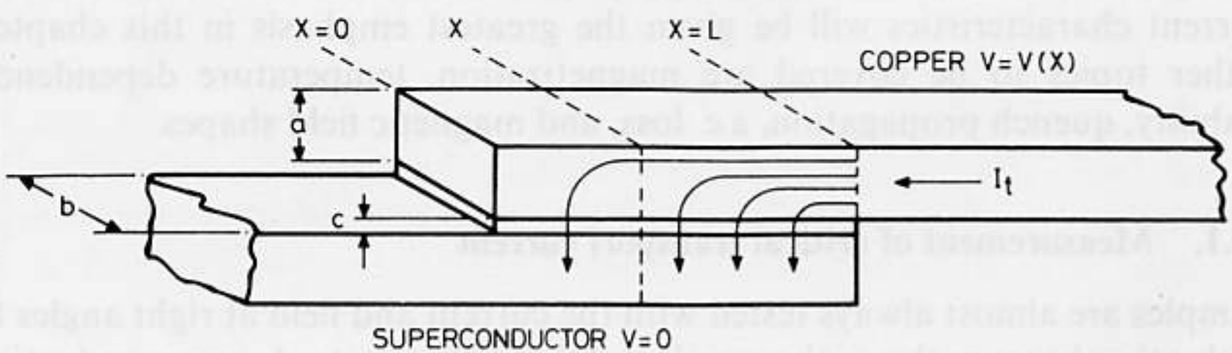
- Must join 10's to ~1000 wires
- Desire
  - Low joint resistance
  - Low ac losses
  - Good current distribution
  - High stability and resistive heat removal

Splice (Joint) Losses

7.3.1 Lap Splice

A "shake hands" lap splice, shown in Fig. 7.2, is one of the most widely used splice designs; it is also quite suitable even for use within the winding. Its dissipation can be set to any desirable level by adjusting the overlap length, ℓ_{sl}.

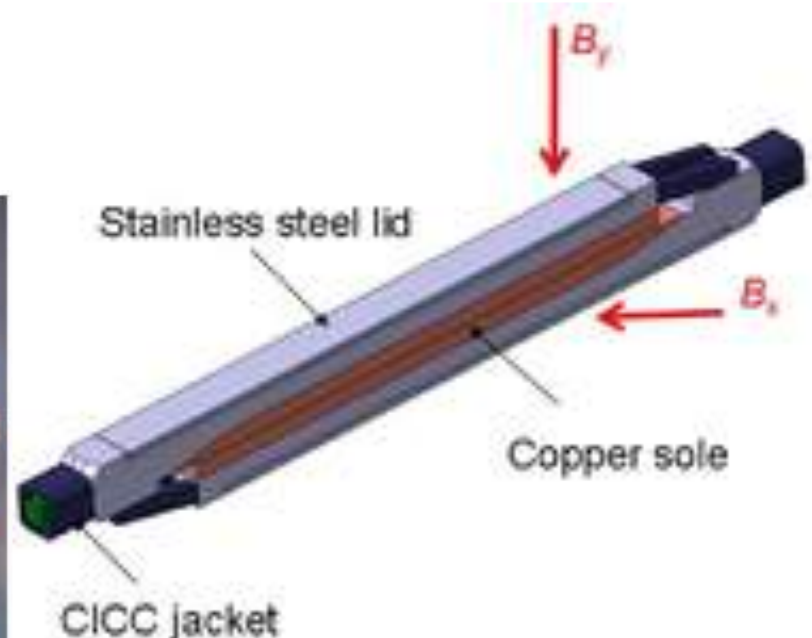




ITER Type CICC Joints

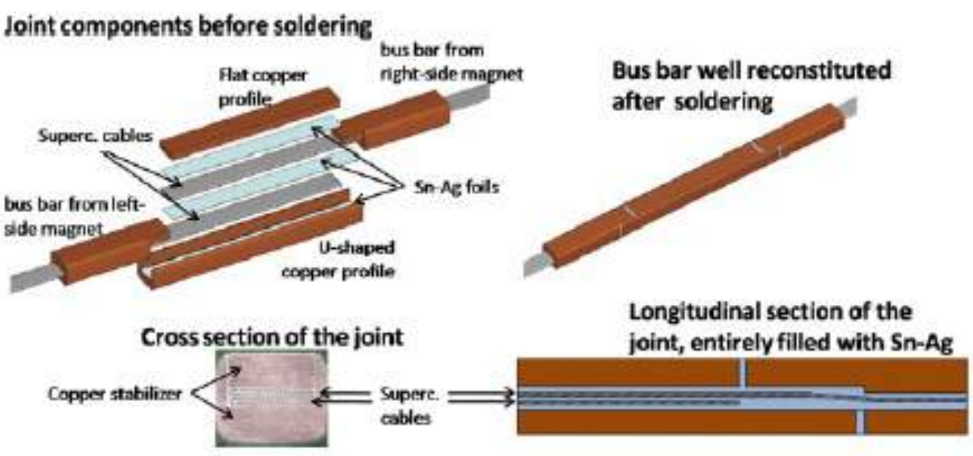
a)

b)



LHC Magnets Splice

- With 1232 main dipoles and ~ 400 quadrupoles a crucial part of the machine is the interconnection between magnets.

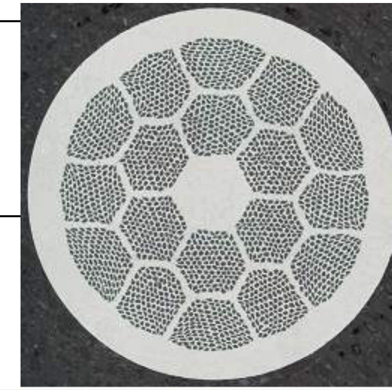


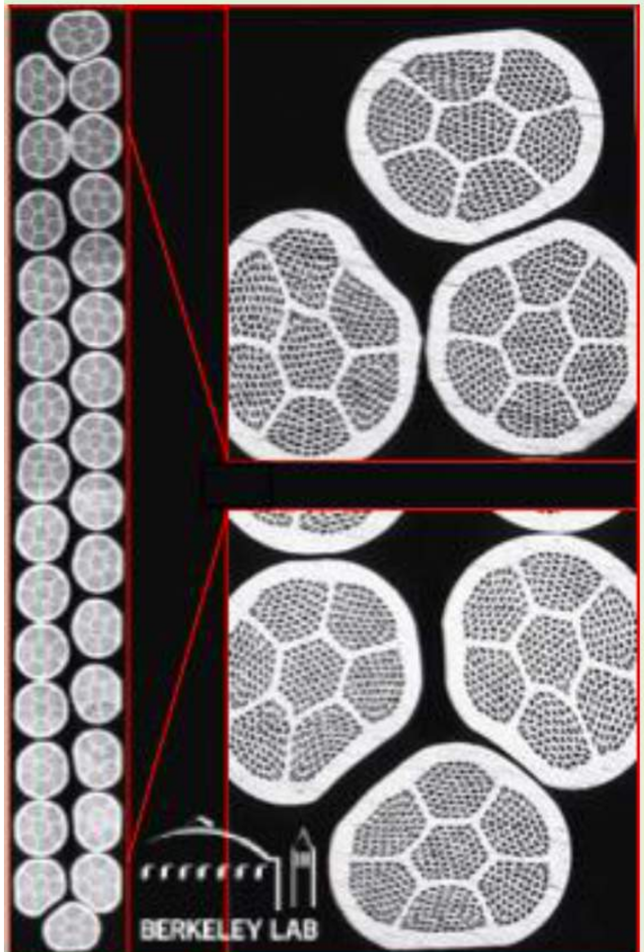
L. Rossi "Superconductivity: its role, its success and its setbacks in the Large Hadron Collider of CERN", Supercond. Sci. Technol. 23 (2010) 034001

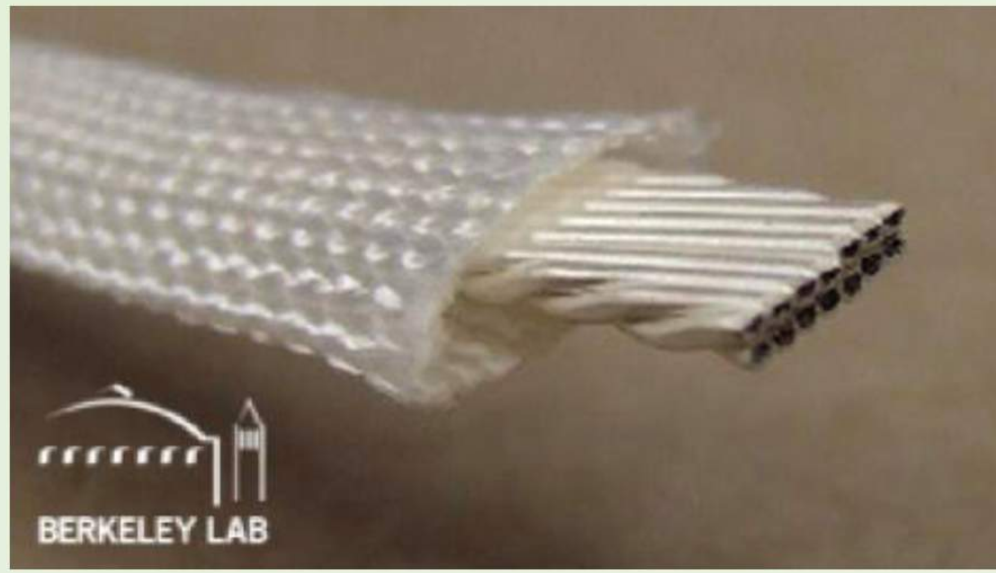
High Temperature Superconducting Cables

- For magnets
  - HEP
    - Bi-2212
  - High Field Research Magnets
    - ReBCO, Bi-2212
  - Fusion
    - YBCO, ReBCO
- For electric power applications
  - Power transmission cables
    - Bi-2223, ReBCO, MgB_2
  - Power Devices
    - Bi-2223, ReBCO

HTS Cables - HEP







Bi-2212 Rutherford cables (Arno Godeke LBNL) with mullite insulation sleeve

HTS Cables - Fusion

HTS Tape Cabling Methods

	Helical winding on a round former		Stacking	
Cabling methods	Winding with a long pitch on a large diameter former.  [2]	Winding tightly with a short pitch on a small diameter former.  [10] **CORC** Conductor on Round Core	Roebel cabling of tapes cut in zigzag pattern.  [5] **RACC** Roebel Assembled Coated Conductor	Twisting stacked tapes.  [22] **TSTC** Twisted Stacked-Tape Cable
Calculated length ratio of cable to tape length	94% - 97% depending on former diameter and winding pitch	40% - 90% depending on former diameter and winding pitch	40% - 89% depending on the number of strands obtained from a original tape	99%

M. Takayasu, et al, *Supercond. Sci. Technol.* **25** 014011, 2012.

[2] J.F. Maguire, et al., *IEEE Trans. Appl. Supercond.* **17** 2034-2037, 2007.
[5] W. Goldacker , et al., *IEEE Trans. Appl. Supercond.* **17** 3396-3401, 2007.
[10] D.C. van der Laan, et al., *Supercond. Sci. Technol.* **24** 042001, 2011.
[22] M. Takayasu, et al, *IEEE Trans. Appl. Supercond.* **21** 2341-2344, 2010.